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Cylindrical Arched Dams of New South Wales, 1896-1908: "Work of a Courageous Nature"

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SUMMARY While single arch dams were built in antiquity, the first application of the thin cylinder formula to arch dam design was the Zola Dam in France in 1854, and possibly the Parramatta Dam in New South Wales in 1856. During the drought and depression of the 1890s, the thin cylinder method was taken up by Cecil West Darley, Engineer-in-Chief in the New South Wales Public Works Department, with a programme of 13 arch dams built between 1896 and 1908 to provide an economical water supply for country towns. These innovative dams broke away from British precedents and generated international interest, and concern, over their radical design.

Darley and his Public Works colleagues were aware of factors not covered by the cylinder formula, but were unable to calculate the mathematical significance of these. That the dams were safe is an historical fact, as all still remain, some for their original use, and others for recreation. Even those which are now silted up are intact despite this overload.

Under the provisions of dam safety legislation in New South Wales, the safety aspects of certain dams have been assessed using modern methods including finite element analysis. Stresses in dams in various locations were found to be close to but within modern criteria. Although none is considered unsafe, their importance as heritage items and the need for high dam safety standards suggests a need also for appropriate and informed management policies. There is a role for professional and government bodies as well as local community groups, with leadership from the Institution. These dams could be a useful medium for furthering awareness of the role of engineering in Australian history, and the significance of engineering heritage.

> "Looking at the cross sections, he would feel a little nervous if he had to sleep on the downstream side of one of the dams: still, they did their work efficiently, though it should not be forgotten that, with the exception of the Parramatta dam, the oldest of the walls had been in existence for only 11 years. It was to be presumed that they were all in open country, where failure would not entail serious loss; if they were in a valley containing a large city or valuable property the question of durability would come in, and he thought it was necessary to be very careful in designing such works, which were intended to last for many years" (W. Hunter in Wade 1909).

The physical forms of these dams on the Australian landscape mark that important transition in the Australian colonies when local needs and conditions were given more weight and solutions from Europe, especially Britain, were less likely to be accepted and applied uncritically. In using a formula largely ignored in 19th Century Europe, engineers of the New South Wales Public Works Department made a significant contribution to the successful revival of a dam design with its source in classical times.

1 THE ARCH DAM IN HISTORY

The first examples of arch dams date from the Roman Empire (at Glanum in southern France and Kasserine in North Africa). In 6 AD the chronicler Procopius of Caesarea recorded an arch dam built on the Turkish-Syrian border, and remnants of the foundations of a Roman arch dam were discovered in France in the 18th Century. The next recorded examples date from c1300 AD, when three cylindrical arch dams were built in Persia under the Mongols. One of these was 60 metres high and remained the world's highest recorded dam until the 20th Century. There were also later examples in Italy and Spain (Schnitter 1976:36).

While the engineers of the Roman Empire used the arch in many different applications and their empirical understanding of the compressed arch is beyond contention, their cumbersome numbering system precluded knowledge of the actual formula.

The first formulation of the resistance of cylinders to crushing pressure was in 1826 when Louis Navier arrived at the formula: $T=\frac{RP}{s}$

where: P = water pressure in tons per square foot; s = safe crushing strength of material per square foot; T = thickness at any point in feet; R = radius in feet (Smith 1971:207; Schnitter 1976:36; Darley 1900:124).

According to Schnitter, in the 1830s, French engineer Francois Zola created designs which apparently for the first time applied this formula to calculate the form of an arch dam. Zola's calculations supposed that the dam consisted of a stack of independent arches, each of which had to resist an increasing pressure depending on its depth below water level. Only one dam was built to this design, the Zola Dam at Aix-en-Provence, begun in 1847 and completed in 1854 (Smith 1971: 182).

Two years later the first arch dam in Australia was completed at Parramatta, 22 kilometres west of Sydney. The 1856 Lake Parramatta dam is considered only the eleventh cylindrical arch dam in recorded engineering history (Schnitter 1976:37). Either this timing was mere coincidence, or the engineer responsible for the design of the Australian dam, Captain Percy Simpson, knew of, and applied, Zola's work. If any documented evidence is found to support this intriguing possibility, the Lake Parramatta dam will be acknowledged as only the second dam in the world built on the cylindrical arch formula (Ash 1986:32).

Currently that place is accorded the Bear Valley Dam in California, designed by F.E. Brown and completed in 1884. This had a considerable technological impact, taking dam design to new limits owing to its unprecedented "bold" slenderness, and high permissible stress allowance of 40 tons per square foot. Brown's primary motivation in choosing the cylindrical arch design rather than a gravity dam was economy; as the site was mountainous, considerable savings were made on the transport, and quantity, of materials (Smith 1971: 207).

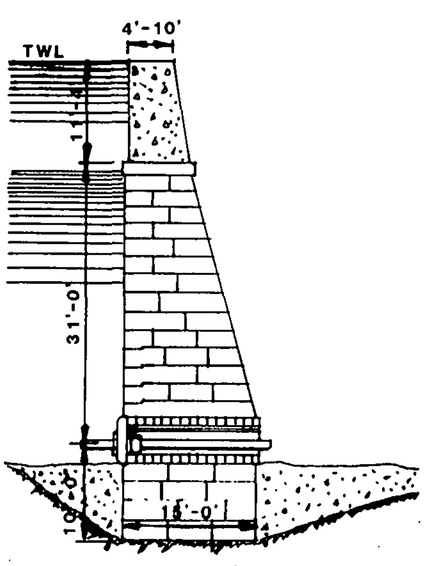

Figure 1

'Parramatta Dam Profile (Wade 1909)

1 inch-16 Feet

Feet 10 5 0 10 20 30 Feet

Scale

2 DARLEY

Lake Parramatta dam might have provided a conceptual example for the adoption of cylindrical dams in New South Wales in the 1890s, but the engineer responsible for adopting this design pointed to Bear Valley as a more immediate source of inspiration. To Cecil West Darley, the innovative American design was an intriguing piece of engineering, but it was the economic advantage in the construction of cylindrical arch dams that prompted its use in New South Wales. As Principal Engineer for Water Supply in the Public Works Department from 1881 until 1889 when he succeeded E.O. Moriarty as Chief Engineer, Darley was well aware that neither the novelty of the design, nor its technological value alone would recommend its application in public works (Darley 1900:xlix-lxii).

Darley had received his engineering education in his native Ireland, and emigrated to New South Wales in 1865. On arrival, he was appointed to the Public Works Department, established only nine years earlier. His career spanned the Department's work from the earlier emphasis on roads, railways, ports and public buildings to the more prominent role given "domestic" works such as water supply and sewerage from the 1880s.

Among Darley's junior engineers were L.A.B. Wade, who in 1896 succeeded Darley as Engineer-in-Chief for Rivers, Water Supply and Drainage, and E.M. de Burgh, Wade's successor. Like Darley, they were part of a transition period in public works engineering, having all begun their careers under the redoubtable E.O. Moriarty. After Moriarty's retirement, Darley, de Burgh and Wade took part in a reorganisation of the Department's engineering branches, the methods of working, and the withdrawal from the heavy reliance on British technology and materials (Maunsell 1985; Coltheart and Fraser 1987: 10).

3 NEED FOR IMPROVED WATER SUPPLIES

The serious shortages of water in Sydney, and the significance for public health of an adequate domestic water supply, were major political issues in the 1880s. In the Australian colonies, as in Britain, sewerage and drainage, as well as water supply works, were seen as the concern of local government. Rapid population growth, a result of the high rate of emigration from industrialising Britain during the 19th Century, meant that need outstripped the financial and administrative organisation for these works. By the late 1870s the serious outbreaks of contagious disease which had plagued Sydney for decades were being repeated in country towns. The small country municipalities were unable either to fund or to construct adequate water supply and sewerage works and the Country Towns Water Supply and Sewerage Act (1880) was the first legislative response to this problem. This Act enabled town councils to raise loans themselves, or to use government finance at low interest with a long repayment period, for water supply schemes built by the Public Works Department and handed over to the councils on completion.

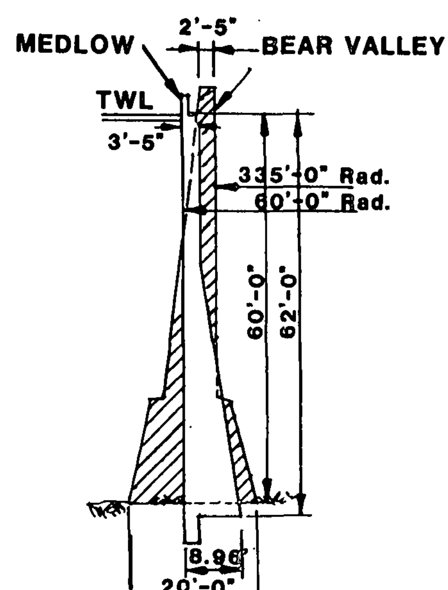

Figure 2 Comparative profiles Bear Valley and Medlow dams (Allan 1916)

The drought in the 1890s worsened the plight of country towns, and the need to accelerate the supply programme despite the economic depression posed a critical public works problem. Loan funds from the Colony's major source, the London market, had dried up as rapidly as had the tanks, lagoons and creeks on which the people in country towns depended. Although provision of water for country towns seems an unlikely government priority during a depression, funds voted for unemployment relief works could be used more efficiently when the work was in country areas, and job creation there reduced the numbers of men seeking work in the city. In fact, all these country towns dams were built by labourers employed by the Department, even when these were not umemployment relief works, as this was found to be more reliable and cheaper than letting the work on contract (Darley 1900:124).

4 SITES FOR ARCH DAMS

Larger towns such as Orange, Armidale and Junee were assessed as able to pay for sizable gravity dams, but these were beyond the reach of smaller towns. The programme could succeed only if capital expenditure on dams was kept to an absolute minimum so that repayment by local councils was feasible. Considering this as an engineering rather than an administrative challenge, Darley recognised the relevance of the Bear Valley precedent. Where there was a fairly narrow gorge with sound rock across and up either abutment, an arch dam could be constructed. For towns with suitable sites nearby, the saving on materials and transporation brought a water supply within their means. The dam at Medlow, in the Blue Mountains west of Sydney, utilised an ideal site allowing a very slender dam profile (Figures 2 and 8). Even where the optimum topography was not available, such as at Tamworth, Wollongong and Parkes, a short length of gravity dam was built at one end and the arch sprung from there, while at Cootamundra two sections of gravity dam were used (Darley 1900:122; Wade 1909:iii).

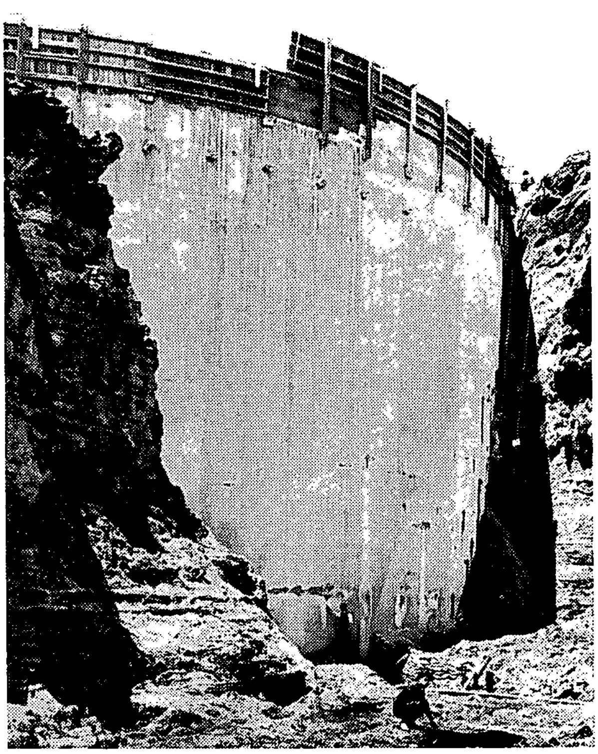

Figure 8 Medlow Dam 1906

Darley's solution initiated the most intensive period of cylindrical arch dam construction in the world. The first was the Lithgow No. 1 dam (Figures 3 and 4), completed in 1896. Within two years four more dams had been built, and thirteen were completed by 1908 (see Appendix 1).

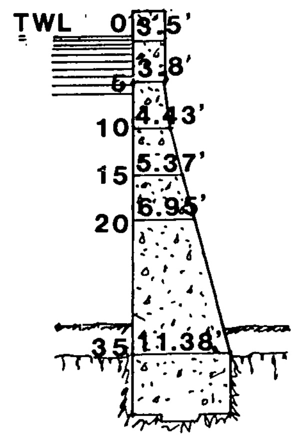

Figure 3 Lithgow No.1 Dam Profile (Wade 1909)

Feet 10 5 0 10 20 30 Feet

Scale 1inch-16 Feet

5 DESIGN

In keeping with the contemporary state of knowledge, the dams were designed as a stack of independent horizontal arches sized soley on the basis of compression of these arches. The maximum economic radius of the curve was limited to 253 feet. For

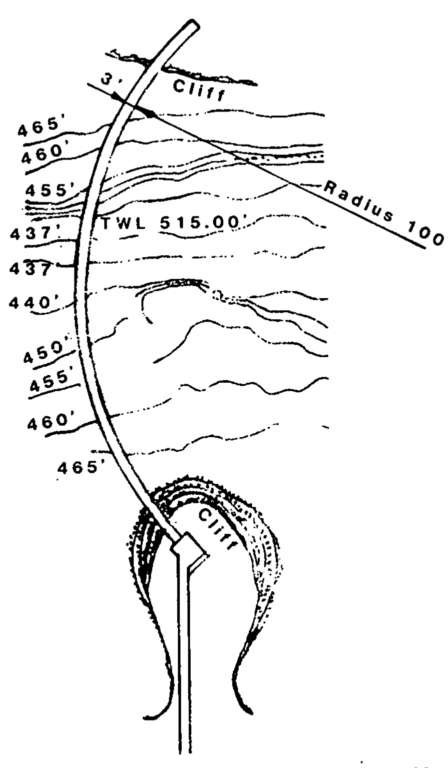

Figure 4 Plan of Lithgow No.1 Dam (Wade1909)

Feet 1050 20 40 100Feet

Scale 1 inch-32Feet

maintenance reasons, and to allow for surcharge, the crest of each dam was made three feet wide. Calculations for determining the thickness of the wall as a function of depth varied according to material properties. Lithgow and Picton dams have sandstone abutments, with a then assumed safe crushing strength of 10 to 12 tons per square foot. At Parkes and Cootamundra, with granite abutments and granite aggregate in the concrete, the limiting pressure was 25 and 24 tons respectively. This compared with 40 tons per square foot at Bear Valley, and allowed a safety factor of 5 on a crushing pressure of 120 tons per square foot. With three later dams, a working pressure of 20 tons per square foot was used before de Burgh decided that 15 tons was the maximum acceptable (de Burgh 1917:85,90; Darley 1900:123-4; B.A. Smith 1920).

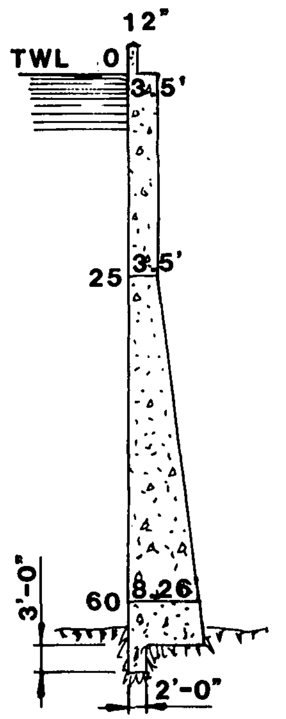

Figure 5 Medlow Dam Profile (Wade 1909)

Feet 10 5 0 10 20 30 Feet

Scale 1 inch-16Feet

The "thinnest" cylindrical arch dam wall in the world at the time is believed to be that built in 1906 at Medlow (Figures 5 and 6). The combination of its height (65 feet) and short crest length with a radius to water face of only 60 feet, made this the most slender cylindrical arch dam ever recorded with its crest thickness 3.5 feet, and base thickness a mere 9 feet. Its working pressure of 12 tons per square foot was, however, relatively low compared to modern dams (Nimmo 1916).

Such slender dam walls caused more than a little disquiet in the engineering world. In London in 1909, Darley read a paper by Wade on the use of these dams in New South Wales, before a meeting of the Institution of Civil Engineers. Many of the professional engineers present argued that the hollow cylinder theory was too simple for application to such a potentially hazardous purpose, while the Medlow Dam was described as "perhaps a little over-bold". It was left to Sir Alexander Binnie, then President of the Institution, to point out the achievement of the Australian engineers:

It was not a matter of cavilling at theory or formulas; the dams had been built and were standing. The problem that now arose was for mathematicians to show how the strains were accommodated in such apparently narrow walls. That they were accommodated was a fact . . . (Wade 1909:32,46).

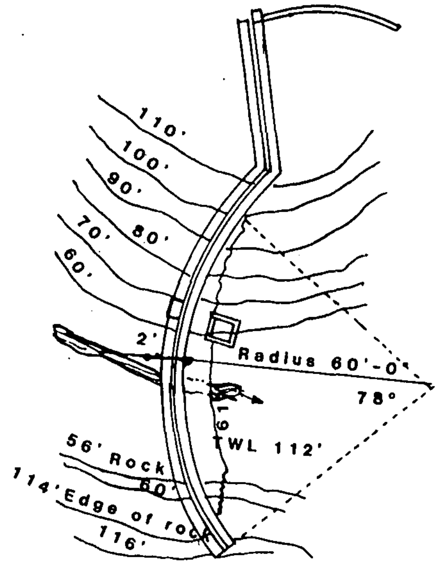

Figure 6 Plan of Medlow Dam (Wade1909)

Feet1050 20 40 100Feet

Scale 1 inch-32 Feet

Darley, Wade and de Burgh were all aware that the dams derived additional uncalculated stability against overturning from their weight, and the fact that they were embedded in the rock strata. However, there is no evidence that uplift pressures were considered. They were unable to shed light on the mathematical significance of these factors, and although later analyses addressed the defects of "ordinary cylinder theory", it is not until now that the mathematical puzzles can be solved, using computer modelling for finite element analysis. Nevertheless, the experience gained by those involved in construction and maintenance of the dams in situ has been important to present understanding of this type of dams' behaviour, a body of knowledge to which these engineers made a unique contribution (B.A. Smith 1920:370).

6 DEFECTS AFTER CONSTRUCTION

In 1909, after construction of the thirteenth dam, Wade reported that the only defects then observed were cracking of the face on five of the dams:

6.1 Parkes Dam (Bumberry)

(Constructed of dry concrete and plums)
A vertical crack from top to base near the deepest portion of the wall - leakage through cracks slight.

6.2 Cootamundra Dam

(Constructed of dry concrete and plums)
A vertical crack from the top to eight feet down - leakage through cracks very light.

6.3 Tamworth Dam (Moore Creek)

(Constructed of dry concrete and plums)
A vertical crack in the curved position at 43 feet

from the abutment, extending from top to base - very slight leakage.

6.4 Wellington Dam

(Constructed of dry concrete and plums)
Eight vertical cracks extending from 8 to 12 feet down from the top - leakage very slight.

6.5 Mudgee Dam (Redbank Creek)

(Constructed of sloppy concrete and plums)
Seven vertical cracks extending from top to base, an average distance of 54 feet apart - leakage slight.

7 PRESENT STATE OF DAMS

Today most of these thirteen historic dams are used only for recreation or emergency supply purposes. Only Medlow, Katoomba and Lithgow No. 2 (with a height of 87 feet the tallest of the dams) are still in use as sources of town water supply. Surveillance reports, required by the Dams Safety Committee of New South Wales (DSC) and regular inspections of the dams by Public Works Department officers (as required under the Local Government, Safety of Dams Amendment Act 1974) reveal that all the dams are still in a safe condition, although the condition of the concrete in many is only fair to satisfactory owing to the presence of various horizontal and vertical cracks with associated leakage and efflorescence. All have some degree of "under dam" foundation leakage, but not sufficient to present any problems.

All the cracks recorded by Wade have since been identified as due to shrinkage. They open and close with changes in temperature and storage level. The only case deemed serious enough to warrant further investigation is the Mudgee (Redbank Creek) Dam, where investigation is currently under way. Interestingly, this was the only one of the dams constructed with "sloppy" concrete, with a view to working up a watertight skin at the faces (Wade 1909: 9,28; Darley 1900:126). The Newcastle earthquake in January 1990, felt in Mudgee with a magnitude of 4.5, appears to have had no significant effect on the dam.

The Tamworth (Moore's Creek) Dam has been completely silted, thus throwing a larger-than-normal load onto the structure. Surveillance inspections reveal that this dam is performing satisfactorily even under this extreme load.

8 MODERN METHODS OF ANALYSIS

Several of the dams have had recent safety reviews using more modern methods of analysis (Public Works Department, NSW 1980;1990).

8.1 "Crown Cantilever" Analysis - Lake Medlow 1980

This method, described by A.L. Parme, shares the water load between the arch sections and the "crown cantilever" (the vertical beam on the centreline of the dam) in such a way that the deflections of the arches are compatible with those of the crown cantilever without attempting to make the deflection of arch sections and all vertical sections equal at all points (Parme 1948).

The analysis showed an area at approximately mid-height of the Lake Medlow Dam where vertical tensile stresses of 1 MPa are calculated to occur on the downstream face. Stresses of this order, which are high, are of concern and horizontal cracking in this area is considered a possibility. The simultaneous surveillance inspection noted only two minor cracks showing leakage. These leaks are in the area of the high tensile stresses at about the mid-height of the dam, and indicate horizontal cracking may have taken place, with the crack extending through the wall. The actual location of any cracks and leaks would depend also on such factors as temperature and depth of water in the dam. These cracks are not considered likely to result in failure of the dam, but some redistribution of loads would result.

The calculations also indicate undesirable tensions and fairly high compressions in the abutments of the lower arches of the dam as well as the toe of the upstream face. Cracking completely through the wall in this zone would appear possible, although there is no indication of leakage or distress at the abutments near the bottom of the dam wall as could be expected if actual stresses approximate those calculated. In fact, some redistribution of loads and stresses would again take place in compensation.

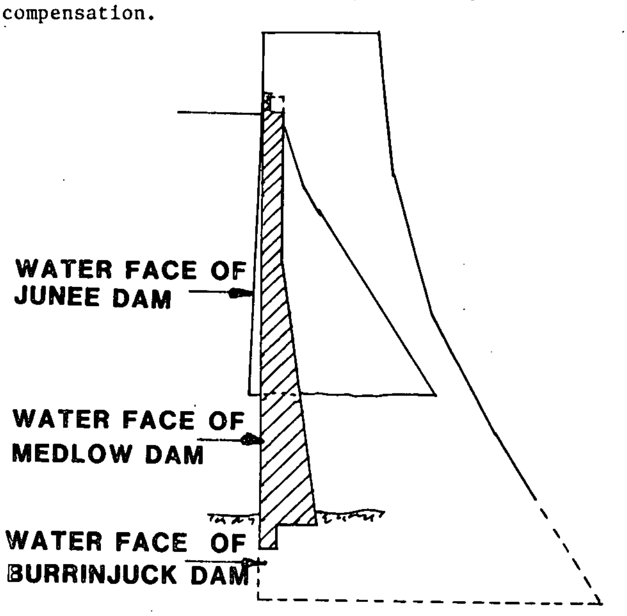

Figure 7 Comparative profiles of Medlow, Junee and Burrinjack Dams (Allan 1916)

8.2 Finite Element Analysis - Lithgow No.1 Dam and Mudgee (Redbank Creek) Dam 1990

A brief finite element analysis, using the desk top personal computer programme STRAND (V.5), was conducted to determine the effect of a more modern analytic technique in assessing the in-situ safety of the historic cylindrical arch dams.

The results showed relatively high vertical tensile stresses in the upstream face of the two dams studied, Lithgow No.1 and Mudgee dams. For the assumption of linear elastic behaviour, these dams appeared to be taking 36.6 per cent and 76.6 per cent respectively of their loads by cantilever action. These differences are reflected in the relative height of dam to crest length ratio (1:4.8 for Lithgow and 1:9.5 for Redbank). As a result, vertical tensions at the upstream face are lower for Lithgow Dam (500 kPa) than for Redbank Creek Dam (650 kPa). Water 1.2 metres over the crest (equivalent to PMF level) for Redbank Creed Dam results in a 40 per cent increase in the maximum vertical tension at the upstream face.

This, however, is an extreme case with an estimated return period of between 15 and 16 years.

With Redbank Creek Dam, a horizontal crack was allowed to emanate from the point of maximum vertical tension at the upstream face. Owing to various limitations, the cracked finite element model was crude. However, it did indicate that once cracking was well advanced, only 50 per cent of the load on the dam was taken by cantilever action (76.7 per cent before cracking). Thus, once horizontal cracking took place, significantly more of the load on the dam was taken by arching action.

Futhermore, the results indicated that even though the dams are relatively highly stressed in vertical tension at the upstream face, the proportions of the load being taken by arching action and cantilever action can be considered of the right order. If cracking at the upstream face takes place, the vertical tensions are relieved and a greater proportion of the load is taken by arching action.

9 MODERN ARCH DAMS CRITERIA

The United States Bureau of Reclamation recommends that the basic tensile strength of concrete be adopted as 5 to 6 per cent of the compressive strength and that, normally, tensile stress should be avoided in design. However, under no circumstances should tensile stress for normal loading exceed 1.03 MPa and for unusual loads 1.55 MPa for arch dams.

Under these criteria, all the above dams analysed would safely comply. Though Medlow Dam under a more conservative method of analysis is very near the limits, it is still acceptable, especially given its age and hence higher expected concrete strength.

At present, there are no plans to remove any of the dams, although further analysis of Mudgee (Redbank Creek) Dam may reveal the need for remedial works to meet the safety criteria adopted by the DSC. However, while the dams appear to be performing satisfactorily, there can be no guarantee of future behaviour and continual surveillance of their physical behaviour is necessary to detect adverse changes.

10 CONCLUSION

The 13 cylindrical arch dams built between 1898 and 1908 began a tradition of Australian arch dam construction which has continued to the present. Of the 50 dams built by 1984, four are over 80 metres high. In this sense alone, the early dams are an important part of Australia's engineering heritage. Each has a unique feature, whether it is Tamworth's lateral gravity section, Medlow's ultra-thin wall, the double-battered experimental wall at Parkes, Mudgee's "sloppy concrete" experiment, or Parramatta, the first arch dam in Australia.

In 1909 James Charles Inglis, President of the Institution of Civil Engineers (UK), referred to these dams as "work of a courageous character" - a phrase which also neatly summarises C.W. Darley's contribution to the construction programme. Approaching the centenary of their construction we can recognise that the courage of these engineers was revealed not only in adopting plans described by their British colleagues as "blood-curdling", but in challenging the British preoccupation with gravity dam design, an emphasis which prevailed in most European countries. Indeed, these 13 dams mark a crossroads in Australian engineering history. The emergent nationalism characteristic of the literature and art of the 1890s also has a clear expression in this recognition but climatic, economic, and engineering problems specific to Australia could be solved by Australian innovation rather than European convention. The cylindrical arch dams in New South Wales are as important a marker of emergent nationalism as the paintings of the Heidelberg school, the poetry of Banjo Paterson, or the bush stories of Henry Lawson. They have a vital, if belated, role to play in raising technological awareness and educating communities about their engineering heritage.

Some of the dams serve a recreational purpose and are already an attraction for local residents and tourists. Their commerical value can be increased through recognition of their historic significance. Even a forgotten dam like Tamworth's silted-up relic could become a local resource with appropriate interpretation and management. All these dams have something to offer the curious visitor, interested in the unique, the unusual, the sites which suggest sense of place and sense of history.

But these are heritage sites with a special problem. While none of the dams breaches the more scientific safety codes today, and modern methods of analysis allow far closer monitoring of their behaviour, safety remains a vital consideration. A dam is always a potential hazard, an old dam even more so. Decisions on the future of these dams will necessarily take into account a safety factor which must be accorded first priority. Such decisions will be made with a far more precise bank of data than was available to the engineers, who designed and built these dams. It is just as important that a comprehensive historical record is available so that these important sites are both safe and significant for future generations. The Institution of Engineers could take the first step by preparing plaques, perhaps to commemorate the centenary of each of these dams, and ensuring local councils, school and community groups become aware of these important local historical resources.

ACKNOWLEDGEMENTS

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APPENDIX 1 - CYLINDRICAL ARCH DAMS CONSTRUCTED IN NEW SOUTH WALES TO 1908 (WADE 1908; DE BURG 1917)

Fig. No. Pl. 1	Locality	Maximum Height above Foundation	Total Length	Top Thickness	Depth below Crest of Top Thickness	Thickness of Base	Surcharge allowed for	Radius of Curved Part	Limit of Pressure in	Approximate Storage	Character of rock forming site and used in construction	Date of Construction	Remarks
		FEET	FEET	FEET	FEET	FEET	FEET	FEET	TONS PER SQ FT	GALLONS			
	Parramatta	52.0	225	4.8	0	15.0	2.0	160	15	130,000,000	Sandstone	-	Original height 41 feet of masonry in Roman cement, built 1858, raised to 52 feet with concrete in 1898.
1	Lithgow No. 1	35.0	178	3.5	3.5	10.88	3.5	100	10	15,000,000	Sandstone	1896	
2	Parkes	33.5	540	3.0	6.0	13.5	5.0	300	24	114,000,000	Granite	1897	
3	Cootamundra	46.0	640	3.0	8.0	13.0	1.0	250	25	136,000,000	Granite	1898	
4	Picton	28.0	112	7.01	0	13.62	10.0	120	12	14,000,000	Sandstone	1897	Constructed to be raised 14 feet when required
5	Tamworth	61.0	440	3.0	3.0	21.5	2.0	250	20	50,000,000	Granite	1898	
6	Queen Charlotte Vale	32.0	113	3.0	6.0	8.65	2.0	90	10	-	Quartzite	1898	
7	Wellington	48.0	350	3.0	7.0	10.0	2.0	150	20	27,000,000	Conglomerate	1899	
8	Mudgee	50.0	498	3.0	5.0	18.0	1.0	253	20	42,000,000	Altered slate	1899	
9	Wollongong	42.0	535	3.5	5.0	11.62	1.0	200	20	160,000,000	Basalt	-	
10	Katoomba	25.0	320	3.0	7.5	20.29	1.0	220	15	34,000,000	Sandstone	1905	Constructed with buttresses. Ultimate height 50 feet.
11	Lithgow No. 2	87.0	221	3.0	3.0	24.0	3.0	100	10	88,000,000	Sandstone	1906	
12	Medlow	65.0	124	3.5	21.0	8.96	3.0	60	12	66,800,000	Sandstone	1906	
13	Mittagong	30.0	173.9	3.6	12.0	6.28	3.0	100	12	7,500,000	Sandstone	1908	